

# THE O VI ABSORBERS TOWARD PG0953+415: HIGH METALLICITY, COSMIC-WEB GAS FAR FROM LUMINOUS GALAXIES<sup>1</sup>

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## ABSTRACT

The spectrum of the low-redshift QSO PG0953+415 ( $z_{\text{QSO}} = 0.234$ ) shows two strong, intervening O VI absorption systems. To study the nature of these absorbers, we have used the Gemini Multiobject Spectrograph to conduct a deep spectroscopic galaxy redshift survey in the  $5' \times 5'$  field centered on the QSO. This survey is fully complete for  $r' < 19.7$  and is 73% complete for  $r' < 21.0$ . We find three galaxies at the redshift of the higher- $z$  O VI system ( $z_{\text{abs}} = 0.14232$ ) including a galaxy at projected distance  $\rho = 155 h_{70}^{-1}$  kpc. We find no galaxies in the Gemini field at the redshift of the lower- $z$  O VI absorber ( $z_{\text{abs}} = 0.06807$ ), which indicates that the nearest galaxy is more than  $195 h_{70}^{-1}$  kpc away or has  $L < 0.04L^*$ . Previous shallower surveys covering a larger field have shown that the  $z_{\text{abs}} = 0.06807$  O VI absorber is affiliated with a group/filament of galaxies, but the nearest known galaxy has  $\rho = 736 h_{70}^{-1}$  kpc. The  $z_{\text{abs}} = 0.06807$  absorber is notable for several reasons. The absorption profiles reveal simple kinematics indicative of quiescent material. The H I line widths and good alignment of the H I and metal lines favor photoionization and, moreover, the column density ratios imply a high metallicity:  $[M/H] = -0.3 \pm 0.12$ . The  $z_{\text{abs}} = 0.14232$  O VI system is more complex and less constrained but also indicates a relatively high metallicity. Using galaxy redshifts from the *Sloan Digital Sky Survey* (SDSS), we show that both of the PG0953+415 O VI absorbers are located in large-scale filaments of the cosmic web. Evidently, some regions of the web filaments are highly metal enriched. We discuss the origin of the high-metallicity gas and suggest that the enrichment might have occurred long ago (at high  $z$ ).

*Subject headings:* intergalactic medium — quasars: absorption lines — quasars: individual (PG0953+415)

## 1. INTRODUCTION

The intergalactic medium (IGM) is an important frontier for studies of galaxy evolution and cosmology for several reasons. The IGM is expected to be the main repository of baryons at all epochs, but the IGM physical characteristics are predicted to change from predominantly cool ( $T \sim 10^4$  K), photoionized gas at high redshifts to predominantly shock-heated “warm-hot” gas ( $T = 10^5 - 10^7$  K) at the current epoch (Cen & Ostriker 1999; Davé et al. 1999). The exchange of matter and energy between galaxies and the IGM, e.g., via gas accretion or supernova-driven “feedback”, may play profound roles in the evolution of galaxies, groups, and clusters (Voit 2005). Observations with the *Hubble Space Telescope* Imaging Spectrograph (STIS) as well as the *Far Ultraviolet Spectroscopic Explorer* (FUSE) have shown

that O VI absorption lines are frequently detected in the spectra of low-redshift QSOs (e.g., Tripp et al. 2000; Danforth & Shull 2005; Lehner et al. 2006). In collisional ionization equilibrium (CIE), O VI has its greatest abundance at  $T \approx 10^{5.5}$  K and therefore can, in principle, be used to detect the warm-hot IGM and hot galactic outflows. However, O VI can also arise in photoionized intergalactic gas or gas that is not in ionization equilibrium, and only a few O VI systems (e.g., Savage et al. 2005) show definitive evidence of hot gas.

One means to investigate the nature and implications of O VI absorbers is to study their relationships with nearby galaxies/galaxy structures (e.g., Sembach et al. 2004; Bregman et al. 2004; Stocke et al. 2006; Prochaska et al. 2006). For this purpose, we have obtained spectroscopic redshifts of galaxies in the fields of several low- $z$  QSOs with the Gemini Multiobject Spectrograph (GMOS) on the Gemini-North 8m telescope. In this *Letter* we report first results from one of the fields observed with GMOS, that of the well-studied QSO PG0953+415.

## 2. DATA

High-resolution UV spectra of PG0953+415 obtained with STIS and FUSE have revealed two strong, intervening O VI absorbers in the PG0953+415 spectrum at  $z_{\text{abs}} = 0.06807$  and  $0.14232$  (Tripp & Savage 2000; Savage et al. 2002). Some improvements in the data reduction procedures, especially in the CALFUSE reduction software, were implemented after publication of those papers, so we have re-extracted the STIS and FUSE spectra as described in Tripp et al. (2001, 2005).

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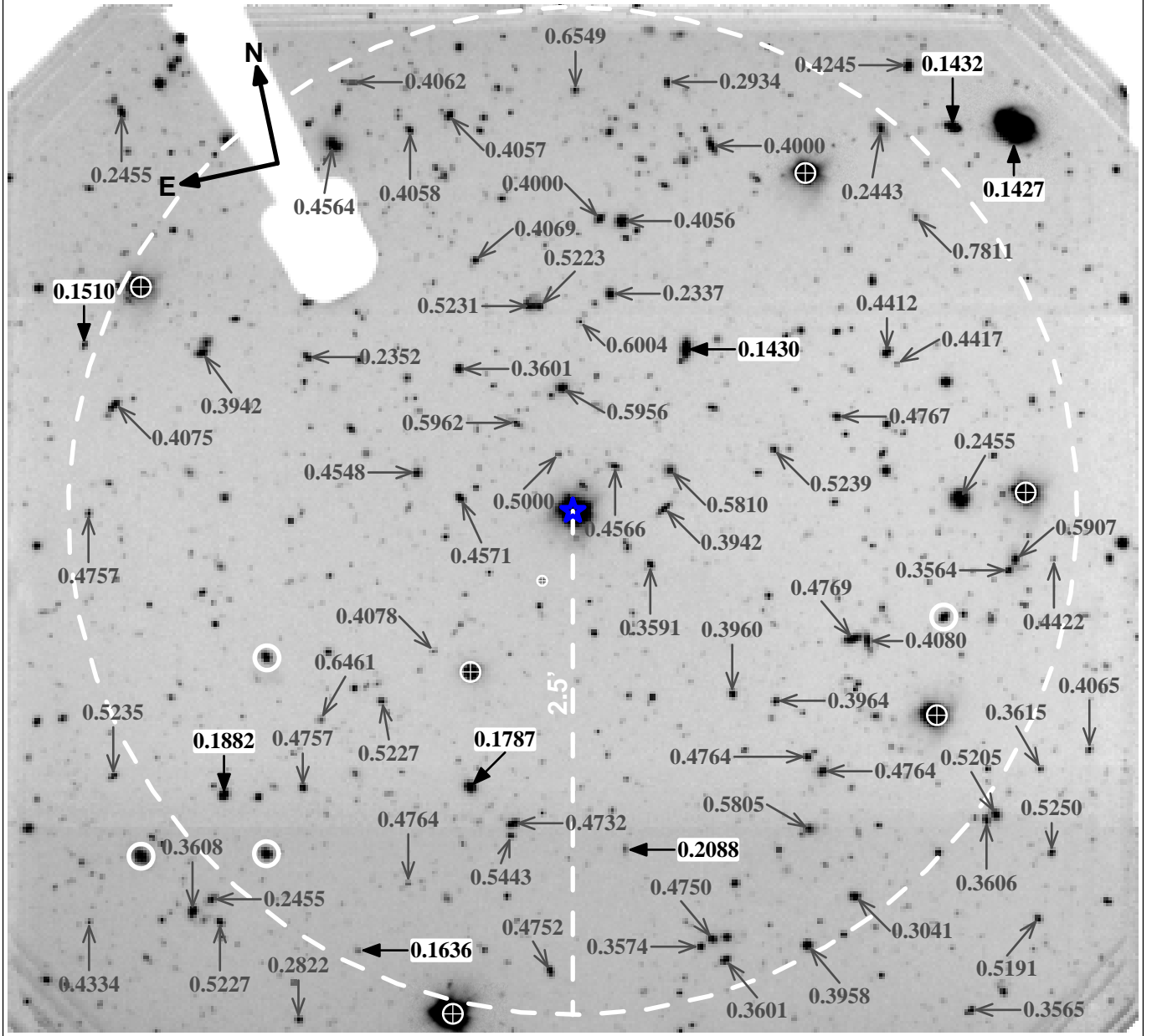


FIG. 1.— **PLATE 1:** Optical  $r'$  image of the PG0953+415 field recorded with GMOS on the Gemini-North telescope. The QSO is in the center, and the white dashed line shows a circle of 2.5 radius. Galaxies are labeled with their spectroscopic redshifts if known. The spectroscopic redshifts place most of the galaxies behind the QSO; redshifts in white boxes indicate foreground galaxies with redshifts that are lower than  $z_{\text{QSO}}$  by at least  $5000 \text{ km s}^{-1}$ . Bright stars are marked with crossed circles. The white region was blocked by the GMOS guide star probe (which could not be positioned outside of the science image). The four brightest galaxies without spectroscopic redshifts are marked with small white circles.

The STIS spectrum has  $7 \text{ km s}^{-1}$  resolution (FWHM) and extends from  $1150$  to  $1730 \text{ \AA}$ , and the *FUSE* spectrum covers  $915 - 1187 \text{ \AA}$  at  $20 - 25 \text{ km s}^{-1}$  resolution. The STIS spectrum has an accurate wavelength scale zero point, and we calibrated the *FUSE* wavelength scale zero point by aligning ISM lines in the *FUSE* spectrum with comparable-strength lines in the STIS spectrum (e.g., Fe II  $\lambda 1144.94$  and Fe II  $\lambda 1608.45$ ). We remeasured absorption-line equivalent widths, column densities, and Doppler parameters, and find good agreement with the measurements reported in Savage et al. (2002). In addition, for the purposes of §3, we have constructed new apparent column density profiles (Savage & Sembach 1991) as follows. In a pixel at velocity  $v$ , the apparent optical depth  $\tau_a = \ln[I_c(v)/I(v)]$ , where

$I(v)$  is the observed intensity and  $I_c(v)$  is the estimated continuum intensity, and the apparent column density  $N_a(v) = (m_e c / \pi e^2) (f \lambda)^{-1} \tau_a(v)$ . The  $z_{\text{abs}} = 0.06807$  system is detected in transitions of H I, C IV, N V, and O VI. Comparison of the doublet  $N_a(v)$  profiles indicates that the C IV and O VI lines at  $z_{\text{abs}} = 0.06807$  are somewhat affected by saturation. For these lines we use the  $N_a(v)$  profiles of the weaker line of the doublet, which provides a conservative lower limit on the column. The O VI  $N_a(v)$  profiles at  $z_{\text{abs}} = 0.14232$  agree within the noise and show no indications of unresolved saturation, so in this case we further used the technique of Jenkins & Peimbert (1997) to construct weighted composite  $N_a(v)$  profiles derived from both members of the doublet.

To study the connections between galaxies and the

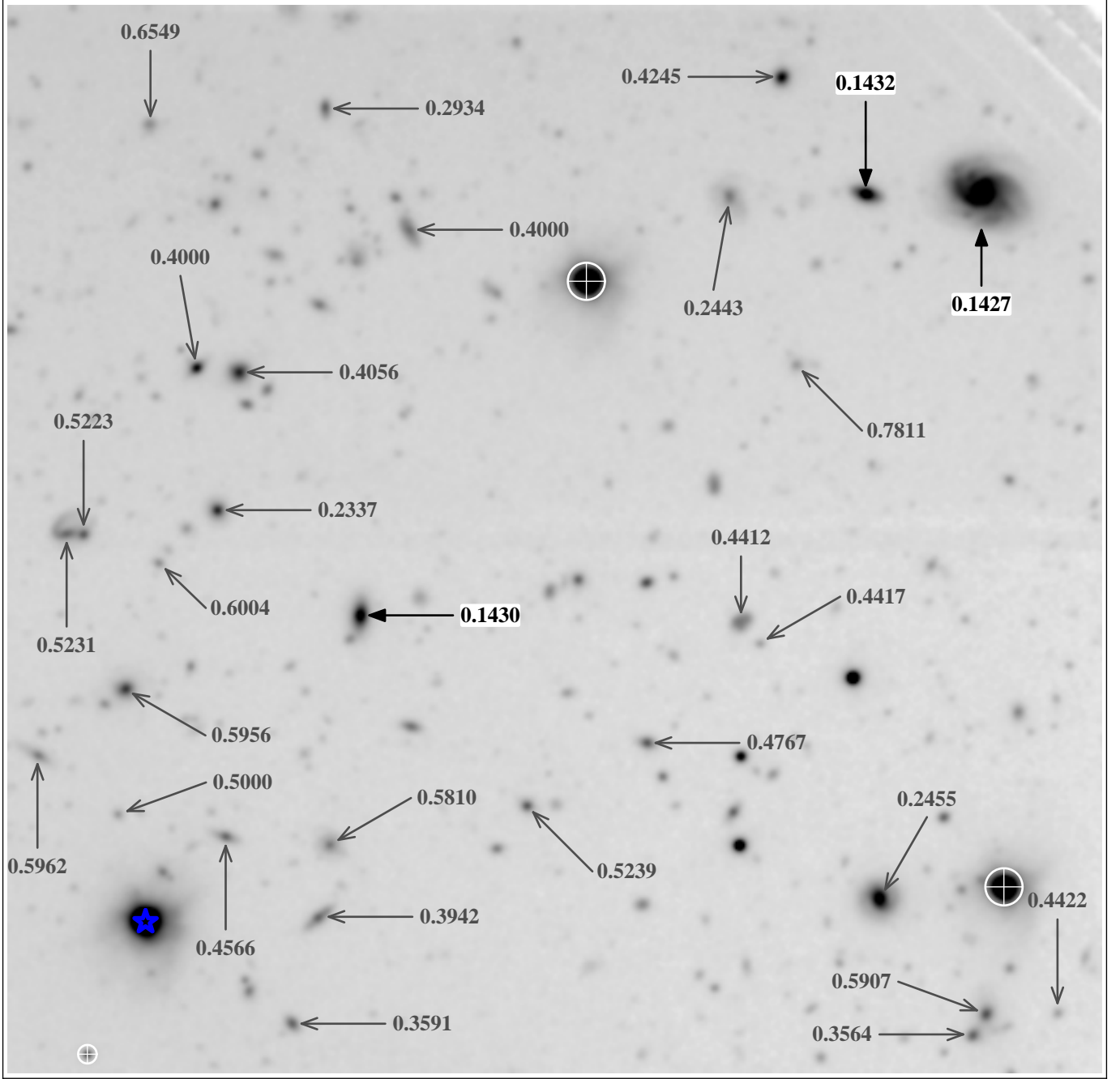


FIG. 2.— **PLATE 2:** Zoom-in on the northwest portion of the GMOS  $r'$  image shown in Figure 1. This figure shows the faint galaxies in the immediate vicinity of the QSO (the point source marked with a star at lower left) as well as the three galaxies at  $z = 0.143$  associated with the O VI absorber discussed by Tripp & Savage (2000). As in Figure 1, redshifts of galaxies foreground to the QSO are marked in white boxes, and crossed circles indicate stars. The contrast in this image is adjusted to better show the morphological structure of the foreground galaxies.

PG0953+415 absorption systems, we have employed GMOS (Hook et al. 2004) on Gemini-North to obtain galaxy redshifts. Full details will be published in a subsequent paper (B. Aracil et al., in prep). In brief, we first obtained a GMOS  $5' \times 5'$  image centered on the QSO in the SDSS  $r'$  filter. The final image was constructed from individual exposures that were dithered to fill in the chip gaps and to allow cosmic ray rejection; the total exposure time was 38 minutes. We used SExtractor (Bertin & Arnouts 1996) to select galaxies from the GMOS image for multislit follow-up spectroscopy with the GMOS R150 grating and the GG455 order blocking filter; this

setup nominally covers the  $4500 \text{ \AA} - 1 \mu\text{m}$  wavelength range with a resolving power of  $\sim 600$ . Targets were prioritized by brightness and proximity to the QSO.

We obtained redshift measurements for 83 galaxies by cross correlation with high signal-to-noise template spectra. To graphically summarize the redshift survey results, Figure 1 (PLATE 1) shows the GMOS image of the PG0953+415 field with the galaxies labeled with their spectroscopic redshifts. Not surprisingly, most of the galaxies are behind the QSO. We find only eight galaxies with redshifts at least  $5000 \text{ km s}^{-1}$  lower than  $z_{\text{QSO}}$ . These foreground galaxies are indicated in white

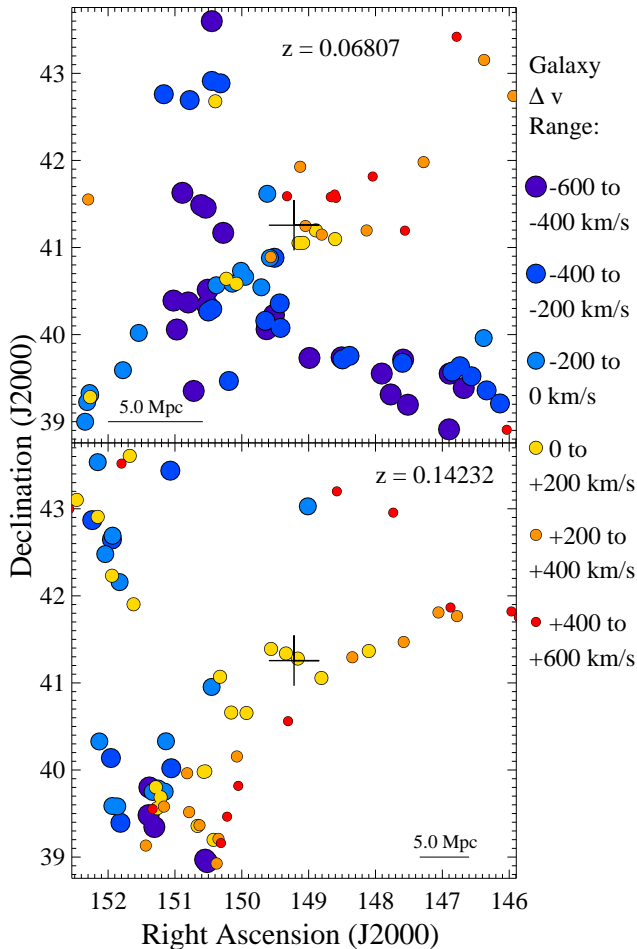


FIG. 3.— Distribution of galaxies in the vicinity of the O VI absorbers at  $z_{\text{abs}} = 0.06807$  (top) and  $z_{\text{abs}} = 0.14232$  (bottom) with spectroscopic galaxy redshifts from the *Sloan Digital Sky Survey* (SDSS). Only galaxies close to the absorber redshifts are plotted, and the symbol size and color indicates the difference between the galaxy redshift and the absorber redshift (in  $\text{km s}^{-1}$ ) as indicated in the key at right (e.g., the largest dark blue symbols mark galaxies with  $-600 < v_{\text{galaxy}} - v_{\text{abs}} \leq -400 \text{ km s}^{-1}$ ). The direction of PG0953+415 is indicated with a large plus symbol, and in each panel a projected distance of 5 Mpc at the absorber redshift is indicated with a labeled horizontal black line. The SDSS data indicate that both of these O VI absorbers are located in large-scale filaments of the “cosmic web”.

boxes in Figure 1. We note that three of the foreground galaxies are near the redshift of the O VI absorber at  $z_{\text{abs}} = 0.14232$  with the closest at a projected distance<sup>4</sup>  $\rho = 155h_{70}^{-1} \text{ kpc}$ . To show the morphology of the three galaxies at  $z \approx 0.143$ , Figure 2 (PLATE 2) presents a blow-up of the NW quadrant of the GMOS image. Figure 2 is also useful for closer inspection of galaxies close to the QSO. Interestingly, the GMOS survey has not revealed any galaxies near the O VI system at  $z_{\text{abs}} = 0.06807$ . Based on the SExtractor galaxy catalog, we find that within  $2.5'$  of the quasar, our sample is 100% complete down to  $r' = 19.7$ , 88% complete for  $r' \leq 20.5$ , and 73% complete for  $r' \leq 21.0$ . At  $z = 0.068$ ,  $r' = 19.7$  corresponds to  $L = 0.04 L^*$ . Savage et al. (2002) have shown that the  $z_{\text{abs}} = 0.06807$  O VI absorber is associated with a galaxy group or large-scale structure, but the

nearest known galaxy in that group has a large impact parameter,  $\rho = 999h_{70}^{-1} \text{ kpc}$ . The new GMOS survey shows that if there is a galaxy closer to the sight line at  $z_{\text{abs}} = 0.06807$ , it is either at  $\rho \geq 195h_{70}^{-1} \text{ kpc}$  or is faint with  $L \lesssim 0.04 L^*$ .

PG0953+415 has also been covered by the *Sloan Digital Sky Survey* (SDSS, Adelman-McCarthy et al. 2006), including spectroscopic follow-up. Figure 3 shows the location of SDSS galaxies at redshifts near the  $z_{\text{abs}} = 0.06807$  and  $0.14232$  absorbers. We only show galaxies within  $\pm 600 \text{ km s}^{-1}$  of each absorber; galaxies with  $z < z_{\text{abs}}$  are shown with blue symbols, and galaxies with  $z > z_{\text{abs}}$  are indicated with orange-red symbols. From Figure 3, it is immediately obvious that both of these O VI systems are found within large-scale galaxy filaments. Both filaments appear to feed into higher density regions as expected in theoretical models (e.g., Davé et al. 1999). Inspection of the three-dimensional SDSS galaxy distribution shows that these filaments are not merely coincidental projection effects; these are real filaments and nodes of the “cosmic web”. The closest galaxy in the SDSS sample at  $z_{\text{abs}} = 0.06807$  has  $\rho = 736h_{70}^{-1} \text{ kpc}$ . Note that the field of view shown in Figure 3 is substantially larger than the field covered by GMOS, but conversely our GMOS survey is much deeper than the SDSS. The SDSS “main galaxy” spectroscopic sample targets galaxies with  $r < 17.8$  (Strauss et al. 2002). This limiting magnitude corresponds to  $L \geq 0.2 L^*$  and  $L \geq 1.1 L^*$  at  $z_{\text{abs}} = 0.06807$  and  $z_{\text{abs}} = 0.14232$ , respectively. The only galaxy in the GMOS field for which SDSS provided a spectroscopic redshift is the extended spiral galaxy in the upper right corner of Figures 1 and 2.

### 3. O VI ABSORBER IONIZATION AND ABUNDANCES

The centroids, velocity widths, and overall line shapes of the H I and metal absorption lines of the PG0953+415 O VI systems are remarkably similar. To show this, we overplot in Figure 4 the apparent column density  $[N_a(v)]$  profiles of the H I, C IV, N V, and O VI absorption lines detected at  $z_{\text{abs}} = 0.06807$  (upper three panels) and the H I and O VI lines at  $z_{\text{abs}} = 0.14232$  (lowest panel). For this purpose, we have scaled the metal  $N_a(v)$  profiles in Figure 4 to match the H I profiles.

Figure 4 provides several valuable observational constraints on the nature of these absorbers. Beginning with the  $z_{\text{abs}} = 0.06807$  system, we see that the metal lines are precisely aligned with the H I absorption and the H I profile is narrow:  $b(\text{H I}) = 21 \pm 2 \text{ km s}^{-1}$ . Notably, the H I lines are far too narrow to arise in collisionally ionized gas in ionization equilibrium at the temperatures expected for O VI. The H I line width at  $z_{\text{abs}} = 0.06807$  implies that  $T \leq 3.8 \times 10^4 \text{ K}$  ( $2\sigma$ ), i.e., an order of magnitude colder than the temperature required to produce O VI in CIE. Moreover, the close match of the H I and the metal  $N_a(v)$  profiles strongly suggests that the H I and metal absorption lines originate in the same (single-phase) gas cloud. The absorption profile simplicity is another useful constraint. The  $z_{\text{abs}} = 0.06807$  system shows mainly one narrow component, which suggests that the absorber is a quiescent, undisturbed entity.

The  $z_{\text{abs}} = 0.14232$  system (bottom panel of Figure 4) is kinematically more complex: at this redshift, six components spread over a velocity range of  $450 \text{ km s}^{-1}$  are

<sup>4</sup> We assume  $H_0 = 70h_{70} \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_\lambda = 0.7$ , and  $\Omega_m = 0.3$  for the calculation of projected distances in this paper.



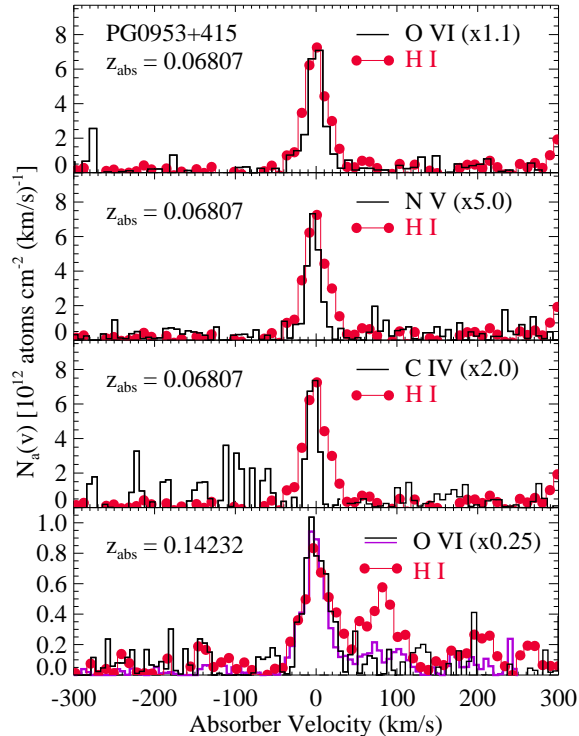


FIG. 4.— Apparent column density profiles of H I, O VI, N V, and C IV transitions observed at  $z_{\text{abs}} = 0.06807$  (upper three panels) and H I and O VI at  $z_{\text{abs}} = 0.14232$  (lowest panel) in the direction of PG 0953+415. The profiles are plotted vs. absorber velocity (where  $v = 0 \text{ km s}^{-1}$  at  $z_{\text{abs}} = 0.06807$  or  $z_{\text{abs}} = 0.14232$ ), and the metal profiles are scaled as indicated in each panel. In the lowest panel, the black line shows the O VI profile derived from the STIS data; the purple line indicates the O VI profile derived from the *FUSE* spectra. The  $z_{\text{abs}} = 0.06807$  N V and  $z_{\text{abs}} = 0.14232$  O VI profiles are weighted composite profiles derived from both lines of these doublets. The  $z_{\text{abs}} = 0.06807$  C IV and O VI profiles are derived from the weaker line of the doublet, which provide a lower limit on the column density. The H I profile at  $z_{\text{abs}} = 0.06807$  is based on the *FUSE* Ly $\beta$  profile, and the  $z_{\text{abs}} = 0.14232$  H I profile is derived from the STIS Ly $\alpha$  line.

present in the Ly $\alpha$  profile (see Fig. 6 in Tripp & Savage 2000). Also, this case affords fewer constraints on the gas ionization mechanism because C IV and N V are not detected. Nevertheless, it is interesting to note that in the main, strongest component (at  $v = 0 \text{ km s}^{-1}$  in Figure 4), the H I and O VI profiles are again seen to have very similar shapes, and again the H I lines are too narrow to arise in CIE [the main component at  $v = 0$  has  $b(\text{H I}) = 28 \pm 2 \text{ km s}^{-1}$ ].

The striking similarity of the H I and metal line profiles and the narrow widths of the H I lines are most easily understood if the gas is photoionized by the UV background light from QSOs/AGNs. In photoionized absorbers, the gas is expected to be cool and quiescent. In principle, these observations could alternatively indicate that the absorbers are not in ionization equilibrium and have cooled more rapidly than they can recombine. Or, these could be multiphase absorbers, and the H I absorption associated with the hot O VI phase is not detected. However, currently available non-equilibrium cooling gas models (Shapiro & Moore 1976; Schmutzler & Tscharnuter 1993) require extraordinarily high metallicities ( $Z \geq 10Z_{\odot}$ ) for agreement with the observed

columns and line widths in the PG0953+415 O VI systems. Based on these models, non-eq. cooling gas appears to be highly unlikely.

Using CLOUDY (v96.01, Ferland et al. 1998), we have revisited the properties predicted for the  $z_{\text{abs}} = 0.06807$  absorber if it is photoionized. We adopt the recent solar abundance revisions (see Table 5 in Savage et al. 2005) and the modified Haardt & Madau (1996) UV background.<sup>5</sup> We find that our updated photoionization model is mostly in good agreement with the results reported by Savage et al. (2002): we find that the logarithmic gas metallicity  $[M/H] = -0.3 \pm 0.12$ , gas pressure  $p/k \approx 1 \text{ cm}^{-3} \text{ K}$ , and absorber thickness  $= 70^{+50}_{-30} \text{ kpc}$ . In §2 we noted that the  $z_{\text{abs}} = 0.06807$  absorption is apparently affected by saturation, and therefore our O VI column could be underestimated. Applying the method of Jenkins (1996) to correct the O VI for saturation, we find that  $N(\text{O VI})$  could be 0.25 dex higher than the value derived from profile fitting and direct integration of the 1037.6 Å line.<sup>6</sup> This would seem to require an even higher metallicity. However, such an increase in O VI would require a higher ionization parameter (and therefore a lower density and larger absorber size) in order to match the resulting increased O VI/N V ratio, and the required change in metallicity would be small. If the  $z_{\text{abs}} = 0.14232$  absorber is also photoionized, then the (albeit more limited) observations again imply a low density and relatively high metallicity (see Savage et al. 2002).

#### 4. DISCUSSION

The PG0953+415 O VI absorbers appear to be photoionized and metal-rich, and yet the nearest galaxies are relatively far from the sight line. Other recent studies of absorber-galaxy connections have found similar results, i.e., high-metallicity, highly ionized gas in large-scale structures but with no luminous galaxies within  $\rho \lesssim 100 \text{ kpc}$  (e.g., Tumlinson et al. 2005; Aracil et al. 2006; Prochaska et al. 2006). The detection of enriched, photoionized O VI absorbing gas is in contrast to the predictions that IGM O VI absorbers arise in collisionally-ionized metal-poor WHIM gas. Our detection of kinematically simple photoionized gas so far from any galaxy also does not conform to the idea that IGM O VI arises predominantly in turbulent collisionally-ionized galactic outflows. How, then, did such chemically enriched gas end up more than 150 kpc away from any known luminous galaxy?

One possibility is that the O VI absorbers arise in material that has been dynamically stripped out of a galaxy. It has long been known that tidally stripped gaseous structures can extend for many tens of kpc (e.g., Yun, Ho, & Lo 1994), and O VI absorption is frequently detected in sight lines through the Magellanic Stream (Sembach et al. 2003), a nearby example of a dynamically

<sup>5</sup> Motivated by Shull et al. (1999), the modified UV background has a steeper EUV spectral index. Use of the original Haardt & Madau UV background with the shallower EUV index increases the derived metallicity by a factor of  $\sim 2$ . We normalize the UV background to  $J_{\nu} = 1 \times 10^{-23} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$  at 1 Rydberg.

<sup>6</sup> The C IV doublet at  $z_{\text{abs}} = 0.06807$  also shows evidence of saturation, but the C IV profiles are too noisy in the line cores to enable a reliable saturation correction using the method of Jenkins (1996).

stripped material. This hypothesis can explain the lack of a nearby luminous galaxy because the donor galaxy could be a faint satellite dwarf which would be hard to detect. The relatively high metallicity of the absorbers can also be understood because tidally stripped material can be significantly enriched (reflecting the metallicity of the progenitor galaxy). Tidal debris is often kinematically complex (e.g., Bowen et al. 1994), and while the  $z_{\text{abs}} = 0.14232$  system shows similarly complex kinematics, the  $z_{\text{abs}} = 0.06807$  absorber does not. In addition, both PG0953+415 O VI systems have much lower H I column densities than well-studied tidal structures. However, *FUSE* observations have revealed absorption at Magellanic Stream velocities without corresponding 21 cm emission (Sembach et al. 2003); much tidal detritus is likely to have H I columns below the 21 cm detection threshold. It remains possible that the absorption arises in the lower-density, more quiescent periphery of a tidal structure. A more substantial problem is that O VI in the Magellanic Stream is believed to be *collisionally* ionized due to interaction between the stream and a hot Galactic halo, and the O VI and low ions in the stream often show different velocity centroids and widths, unlike the PG0953+415 O VI systems. However, some Magellanic Stream clouds are kinematically simple and even show C I and H<sub>2</sub> absorption lines (Sembach et al. 2001), so tidal stripping can be a gentle process for at least some of the stripped gas. Once the density of the tidal debris drops sufficiently, it will become highly ionized by UV background photoionization.

However, galaxies are known to show a correlation between metallicity and luminosity (Tremonti et al. 2004, and references therein), so if the PG0953+415 O VI systems were stripped out of a low-luminosity dwarf, one might expect the absorbers to have a lower metallicity. An alternative hypothesis is that the PG0953+415 O VI absorbers might have been mainly enriched by processes that occurred at high redshifts. Recent studies indicate

that star-forming, high- $z$  galaxies can have near-solar metallicities at  $z > 2$  (e.g., Pettini et al. 2002; Shapley et al. 2004; Erb et al. 2006), and Simcoe et al. (2006) have reported evidence that QSO absorbers have high metallicities within 100-200  $h_{70}^{-1}$  kpc of high- $z$  galaxies. This hypothesis can explain the absence of a nearby galaxy in the case of the  $z_{\text{abs}} = 0.06807$  absorber toward PG0953+415: if the enrichment occurred at  $z \gtrsim 2$ , then the source galaxy could have moved a substantial distance away from the sight line during the time that has passed since the metals were injected into the IGM. In this hypothesis, the metals could have been removed from the source galaxy by a supernova-driven outflow or by dynamical stripping; in either case the enriched gas could settle into a quiescent state and thereafter remain highly ionized due to photoionization by the UV background. To test these ideas, it would be useful to measure the metallicities of the nearest galaxies. The three galaxies closest to the  $z_{\text{abs}} = 0.14232$  absorber (see Figure 2) are all emission-line galaxies, as are some of the closest galaxies at  $z_{\text{abs}} = 0.06807$  (see Aracil et al., in prep). Comparison of the galaxy and absorber metallicities would provide additional constraints on the possible origin of the enrichment.

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